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Analysis of Water Flows in the Interior Niger Delta of the Niger River during the Period 1980-2019 in Mali

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Abstract

This study is based on the analysis of the water flowing of six hydrological stations in the Interior Niger Delta of the Niger river during the period 1980-2019, these stations are Ke-Macina, and Douna stations at theat entrance to the interior Delta, Sofara and Moptistations the center of Delta, and Akka and Dire stations the exit of the Inner Delta of the Niger River. This area is located in the semi-arid Sahelian zone. It is a vast flooding zone of approximately 40.000 km^2 which stretches along a South-West and North-East axis (from Ke-Macina to Tombouctou) over more than 350 km between the parallels 17° and 13° North and the meridians 2°30 and 6°30 West. The highest value of the annual flood flow is observed at the Ke-Macina station with a water flow of 2173.99 m^3/s and the lowest value of the flood recession flow is observed at the Douna station with 18.94 m^3/s. From January to May, there is a decrease in the monthly water flow, in March with a value of 14.50 m^3/s at the Sofara station. From the month of June, there is an increase in the monthly water flow to reach the flood flow during the months of September for the stations hydrological of Ke-Macina, Douna and Sofara and the month of October for Mopti station and November for Akka and Dire stations. The highest monthly water flow is observed at the Ke-Macina hydrological station with a value of 3137.74 m^3/s. On all the six hydrological stations, the following observations are made: the period 1982-1993 constitutes the dry period and the period 1994-2019 is the wet period, except for a few years.

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Introduction

The water resource management is a need that is expressed at all levels (local, national, regional and global) due to the often-dramatic consequences of a shortage in human and economic terms. However, you can only manage a resource well when it is under control. The analysis of water flow is extremely important for the management and planning of water resources. Water is the basic building block of life. Drinking water and sanitation are essential for life and health and essential for the dignity of all (WHO, 2011). The Earth is the only planet in the Solar system to have liquid water on its surface, thanks to its privileged position. The water molecule is essential for the development of life. Habitat of part of the fauna and flora, source of hydroelectricity generation so the water is essential element in agriculture, vital element of food.

It water becomes more and more a coveted commodity, with the increase of the world population. Especially since fresh water, the main issue of lust, only constitutes 3% of the world's water resources and the rest being formed by seas and oceans. The three-quarters of water ressources are stored in the form of ice (Lienou Gaston, 2007). However, fresh water represents less than 1% of the planet's resources, the rest being divided between ocean salt water (97.5%), glacier and polar ice cap water (1.8%) and water vapor in the atmosphere (0.001%) (Magand Claire, 2014).

The Water is therefore an abundant resource, renewable but unevenly distributed on the surface of the Earth. Runoff seems to increase in high latitudes and in the United States, while it decreases around the Mediterranean basin and in West Africa (NGOs, 2014). The interior Delta of the Niger River is one of the largest flooding regions in the world. It is on the southern border of the Sahara, where rainfall is limited; wetlands are therefore dependent on the water supply from the river. The water level in the interior Delta therefore also varies between 4.5 and 7 meters depending on the year. The flooded area of the Delta then varies according to the years between 10000 and 45000 km^2. Almost a million people like fishermen, breeders and farmers live at the expense of the Delta whose usable area covers 50000 km^2 (Eddy Wymenga *et al.*, 2001). The flow of water from the Niger river in the interior the Delta is known and its duration varies between 5 to 7 weeks depending on whether the flood is good or weak (Eddy Wymenga *et al.*, 2001). The hydrological balance in the interior Delta is established by difference between the water flow entering to the hydrological stations of Ke-Macina and Douna for Niger and Bani its principal affluent and the flow leaving the Dire station (Mariko *et al.*, 2004). The hydrological regime is largely dependent on water resources from the much morerainy regions watered upstream hydroclimatic regimes of the upper Niger and Bani basins. The precipitated annual water heights experienced sharp decreases. The deterioration in the climatological situation which dates back to the beginning of the 1970 has resulted in rainfall deficits of up to 20 to 25% and deficits in average annual water flow of 40 and 60% during the dry period (Mariko *et al.*, 2004).

Presentation of the Study Area

The study area is located in West Africa, in the center of Mali. It is nommed the Niger interior Delta of Niger river. The study covers the period 1980-2019 and concerns the water flow at the entrance inthe center and at the exit the interior Niger region. From Segou for Niger and Douna for Bani, the course of Niger enters a huge alluvial plain filled with different deposits of the quaternary. This area, known by the different names: Central Delta, lake basin, interior basin or interior Niger river Delta (Cécile Picouet, 1999). The interiorNiger River Delta in Mali is a vast spreading plain of the waters of Niger and Bani, which is located between 13°and 17°N and 2° and 6.5° W. It covers an area of approximately 50000 km^2 (Mahe *et al.*, 2011). It stretches along a rectangle-oriented South-West / North-East over more than 350 km between Ke-Macina and Douna hydrological sites to the south and Dire and Tombouctou hydrological sites in the north (Mariko *et al.*, 2004).

The Niger interior Delta corresponds geographically to the maximum extension of flood waters and peripheral lakes. It is limited:

to the East and to the South, by the reliefs of the Bandiagara plateau,

to the West, by the "Dead Delta", an area of ancient deposits above the current Delta,

and finally, to the North, by a series of dunes oriented in the East-West (direction) (IRD and UNESCO, 2012).

It is located between the regions of Djenné, Mopti, Tenenkou, Youwarou and Dire and convered44 municipalities and 821 villages for a population of1730223 habitants. Flooding depends on the rainfall of the upper basins of Niger and Bani. The local rains contributing only for 5 to 10% of the water flows (Aïda Zare, 2016). TheNiger interior Delta shows four main morphological types with distinct characteristics High Delta, Middle Delta, Lower Delta and North of the dune (or erg of Niafounke). More simply, we will retain:

An upstream and central part downstream of Ke-Macina and Douna hydrological stations with the creation of two major branches: Niger and Bani rivers for Malian Mesopotamia around Djenne for the Upper Delta, Niger river and Diakka for the Kotia plain in the Middle Delta. extends to the central lakes (Lac Debo, Lacs Wallado and Korientze) and is made up of large areas of spreading still largely flooded by the annual flood.

A downstream part which extends from the exits of the central lakes, with three main draining axes which are

Issa Ber, Barra Issa andKoliKoli to Diré, where a very different geomorphology, characterized by an overlay on the anterior deltaic forms of an oriented Erg Holocene East-West, leads to observe a very diffuse hydrological network, often controlled by the inter-municipal furrows, with more reduced flood zones, but peripheral lakes fed during strong floods (Cécile Picouet, 1999). The climate is influenced by the Harmattan (trade winds), dry air from the North Africa high pressure and by the monsoon (humid air from the South).

The Intertropical Front separates these two air masses. Its North-South movements determine the rainy season. There are different seasons. Which are a cool and dry season from November to March, a hot and dry season from April to June, a rainy season from July to September and a second hot season after the rains in October. from 700 mm in the south to 300mm in the North of the Delta.

The maximum average rainfall is in August. The Niger interior Delta is an ecosystem in which the hydrological regime, the dynamics of the natural environment and human activities as good as fishing, agriculture and animal husbandry are closely associated (Mariko *et al.*, 2004).

The hydrological cycle of the interior Niger Delta extends from July to next June. In the central part of the Delta, it is in May and June that the water level is at its lowest stage: low water. Between July and October, the flood rises to reach its maximum level in November-December.

The recession extends from January to April. (Eddy Wymenga *et al.*, 2001) In addition to direct precipitation and a few sporadic waters flows from the Bandiagara plateau and small watersheds bordering the river, the contributions to the Niger Inner Delta and Middle Malian Niger mainly come from catchment areas of upper Guinean and Malian Niger (3/4) and Bani (1/4).

Data and Methods

The hydrological data are made available from the National Directorion of Hydraulics of Mali. These data relate to monthly and annual water flows. The hydrological network chosen for our study consists of six hydrological station sites. These stations are those of Ke-Macina and Douna at the entrance to the interior delta of the Niger River, Sofara, Mopti and Akka hydrological in the center of the Delta and Dire hydrological station sites at the exit of the Delta region site. The coordinates of the hydrological observation stations are given in the following table.

Materials and Methods

Two methods have been used: a graphical method based on the analysis of the evolution of the debit indices, weighted moving averages and drying coefficients and a statistical method based on the use of statistical tests of homogeneity (detection of ruptures) and trend.

Nicholson index

The Nicholson index measures the deviation from a long-term average based on station data. The annual debit index is the reduced central variable of annual debit. It is obtained by calculation using the following formula:

$$Ip=\frac{X_i - X_p}{\sigma}$$

Where: X_i is water flow for year i considered year i; X_p is the average interannual water flow over the study on considered period;σ is the Standard deviation of the interannual water flow over the study on considered period; and Ip is the variation index.

Standard deviation

The standard deviation (σ) corresponds to the square root of the sum of the squares of the differences between the monthly values of an observed parameter x_i and the station average $\bar{x}$ multiplied by the number observations x_i divided by the sum number of observations by the sum is given. Its formula is:

$$\sigma=\sqrt{\frac{\sum((x_i-\bar{x}))^2 n_i}{\sum n_i}}$$

Where: the standard deviation σ correspond to square of the sum of the squares of the difference between the monthly values of an observed parameter n_i and the station average $\bar{x}$ all multiplied by the number of observations n_i divided by the sum of the same number.

Variance

The coefficient of variation (V%) is given by:

$$V\% = \frac{\sigma}{\bar{X}} * 100$$

Results and Discussion

This part, results and discussions, includes the interannual variations of the standardized flow index (SPI) of the six hydrological stations which are Ke-Macina and Douna at the start of the Delta and Dire at the exit.

The highest water flow variation is observed at the Douna hydrological station and the lowest variation is observed at the Dire station. For the six hydrological stations studied, the coefficient of variation of the stations studied is greater than 19.25%.

Interannual variations of the water flows

The interannual variations in water flows during 1980-2019 are shown in the figure 2 above and show considerable variability from year to year. The annual flows vary greatly at all the hydrological stations of the study.

For the Ke-Macina station, the average interannual flows vary between 2173.99 m^3/s and 504.77 m^3/s. The flood flow is observed in 2019 and the low flow is observed in 2004. From 1981, an alternation between the flows is observed. All annual flows are greater than 500 m^3/s.

The following observations are made, at the Dounahydrological station, the annual average flows vary between 873.73 m^3/s and 18.94 m^3/s. The flood flow of the Douna station was observed in 2012 and the low flow in 1998. For the period 1981-1998, the flows are lower than 500m^3/s but beyond 2006, we observe a water flow which is higher at 500 m^3/s.

At the hydrological Sofara station the following observations are made: The lowest annual water flow is observed in 2009 with a value of 36.77 m^3/s and the highest value of the annual water flow is observed in 2018 with a value of 425.07 m^3/s. Except for the year 2009, all flows are greater than 50 m^3/s. At the hydrological Mopti station, the flood flow is observed in 1994 with a water flow of 1082.58 m^3/s and a low flow of 425.17 m^3/s in 1984. All the annual water flows are greater than 400 m^3/s.

At the hydrological Akka station region of Youwarou, the flood water flow is observed in 2019 with a water flow of 1893.79 m^3/s and the low water flow is observed in 1984 with a water flow of 444.01 m^3/s.

For the hydrological Diré station, that is to say, the outlet of the interior Delta, the average annual water flows vary between 990.43 m^3/s and 455.75 m^3/s. The flood water flow is observed in 1995 and the low water flow is observed in 1984.

At the two entrances stations of the Niger interior Delta, Douna and Ke-Macina hydrlogical stations, most of the water flows supplying the inetrior Niger Delta comes from the Upper Niger Basin and the rest from the Bani which is one of the major tributaries of the Niger River. The water flow at the exit of the Niger interior Delta of the Niger River, that is to say at the hydrological station, the average annual water flows are greater than 400 m^3/s.

Monthly flow rate variations of the water flows

The monthly variations of the water flow of the six hydrological stations during the study period 1980-2019 are mentioned in the figure 3 below.

At the Ke-Macina hydrological station, from January to May, there are very low water flows and the low flow is observed during the month of April with a value of 51.41m^3/s but from the month of June there is an increase in the flow and the peak is reached during the month of September with a flood flow of 3137.74 m^3/s. Beyond the month of September, a decrease is observed.

At the Douna hydrological station, there is a decrease in water flow from January to June but from July, there is an increase in flow to reach its maximum in September with a value of 1370.50 m^3/s. Beyond the month of September, a decrease is observed until January.

At the Sofara hydrological station, the following observations are made; from January to June, there is a decrease in water flow; and in the month of July, the flow increases to reach its maximum value during the month of September with a value equal to 745.29 m^3/s. The lowest monthly value of water flow is observed during the month of May with a value of 14.50 m^3/s. Beyond the month of September the decrease is observed.

Table.1 Their geographic coordinates and their chronicles

Hydrological Stations	Stations names	Geographic coordinates		Chronicles
		Longitudes	Latitudes	
Hydrological stations	Ke-Macina	5°21'28,48"W	13°57'50,76"N	1980-2019
	Douna	Not available	Not available	1980-2017
	Diré	-10°58'0,01"W	12°16'59,99"N	1980-2019
	Mopti	14°29'3,48"W	4°10'58,66"N	1980-2019
	Sofara	4° 13′ 52″ W	14° 01′ 03″ N	1980-2019
	Akka	Not available	Not available	1980-2019

Source. National Direction of Hydraulics of Mali (2020)

Table.2 Coefficient of variation of the study stations

Hydrological Stations	Ke-Macina station	Douna Station	Sofara Station
Coefficient of variation	31.66%	70.23%	44.56%
Hydrological stations	Mopti Station	Akka Station	Dire Station
Coefficient of variation	24.69%	37.35%	19.25%

Fig.1 Geographical location of the InteriorDelta of Niger river (IRSTEA, 2014).

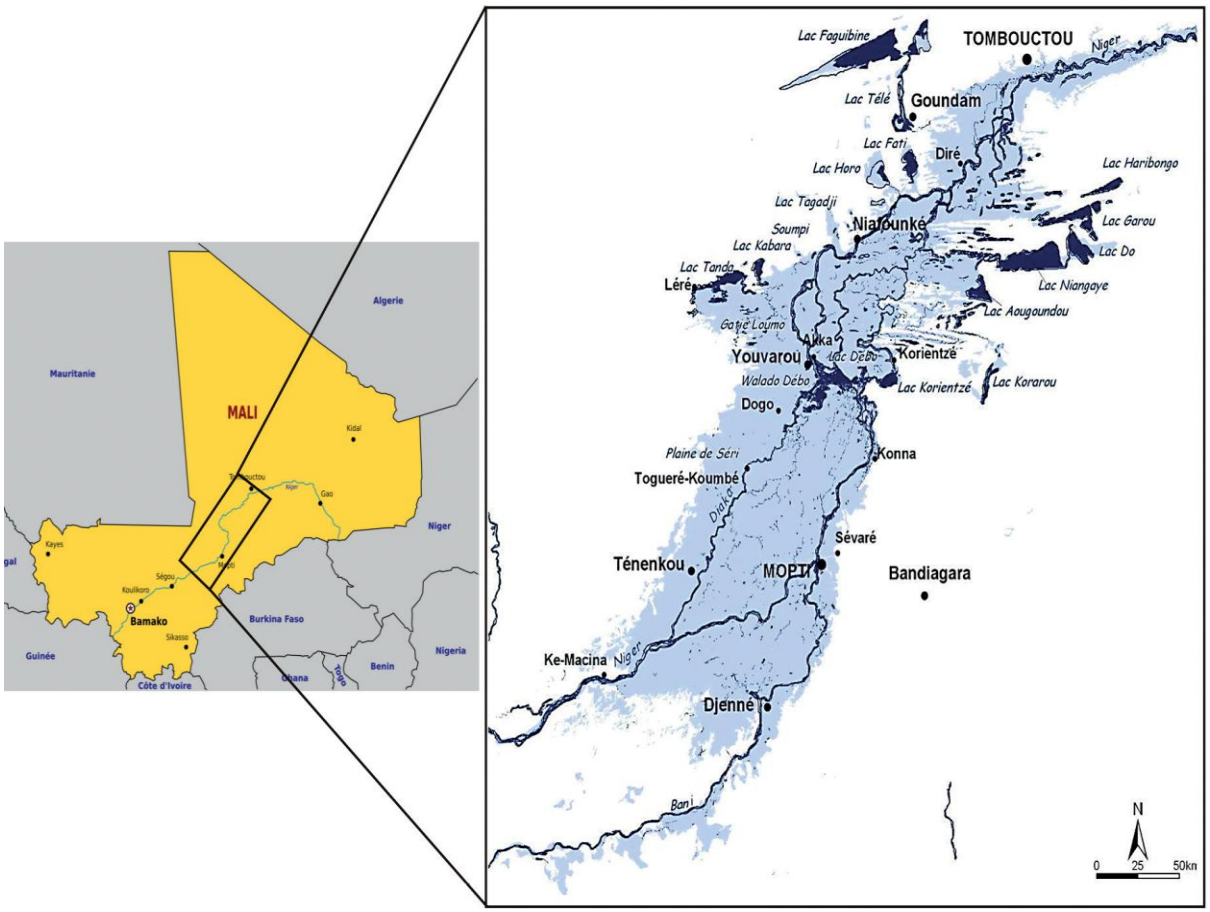


Fig.2 Interannual water flow variations of the six hydrological stations during the study period 1980 – 2019.

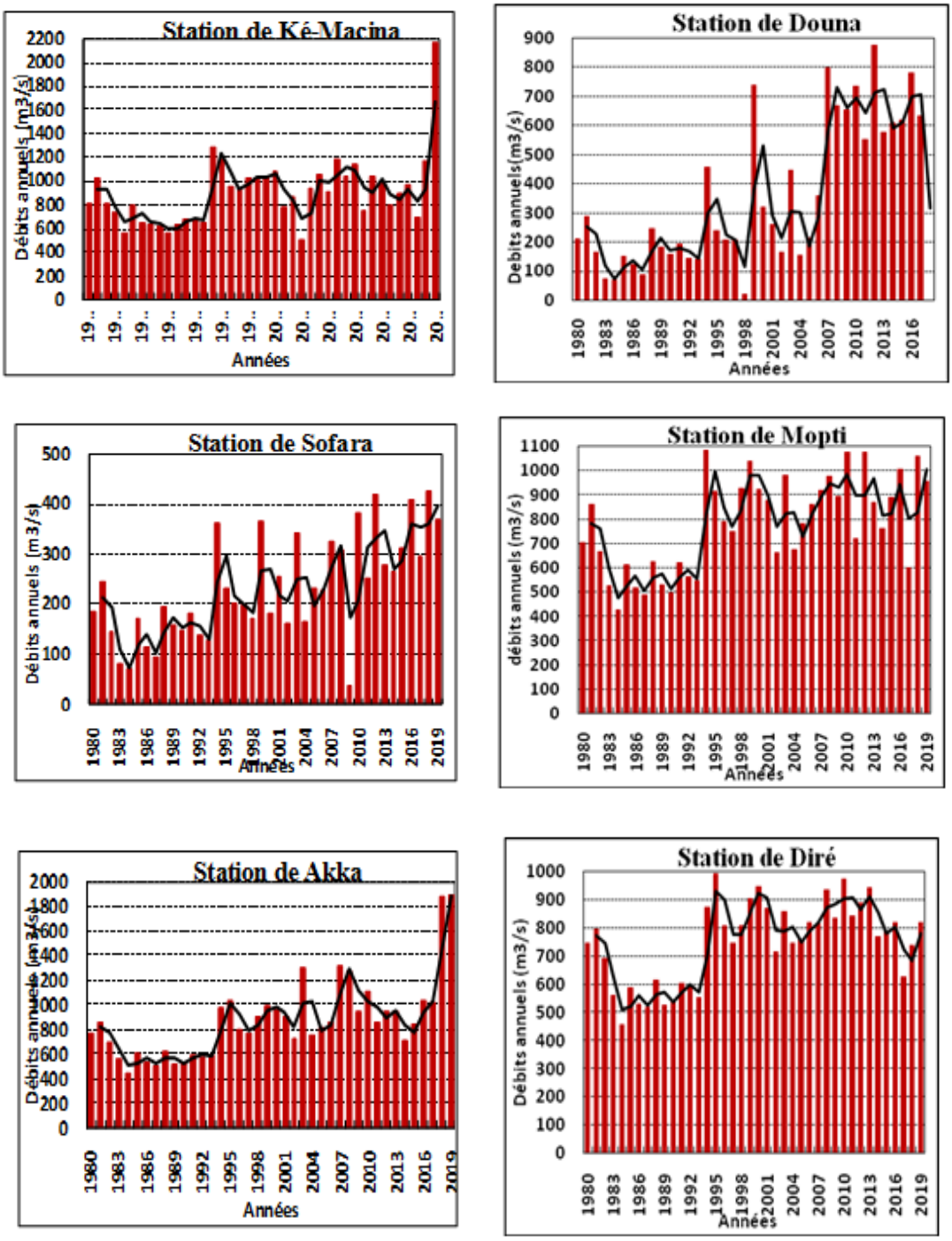


Fig.3 Monthly variations of water flow of the six hydrological stations during the study period 1980-2019.

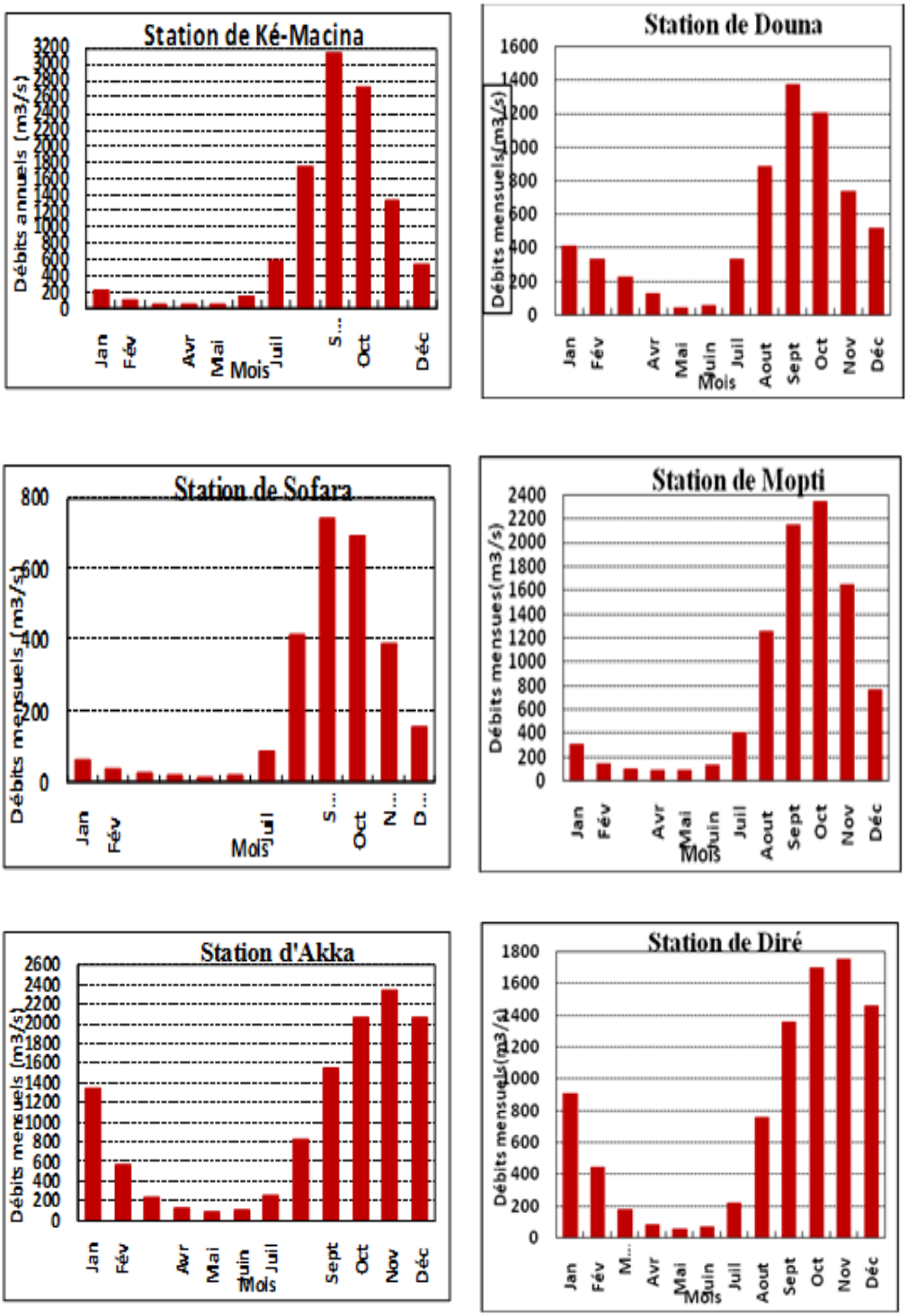
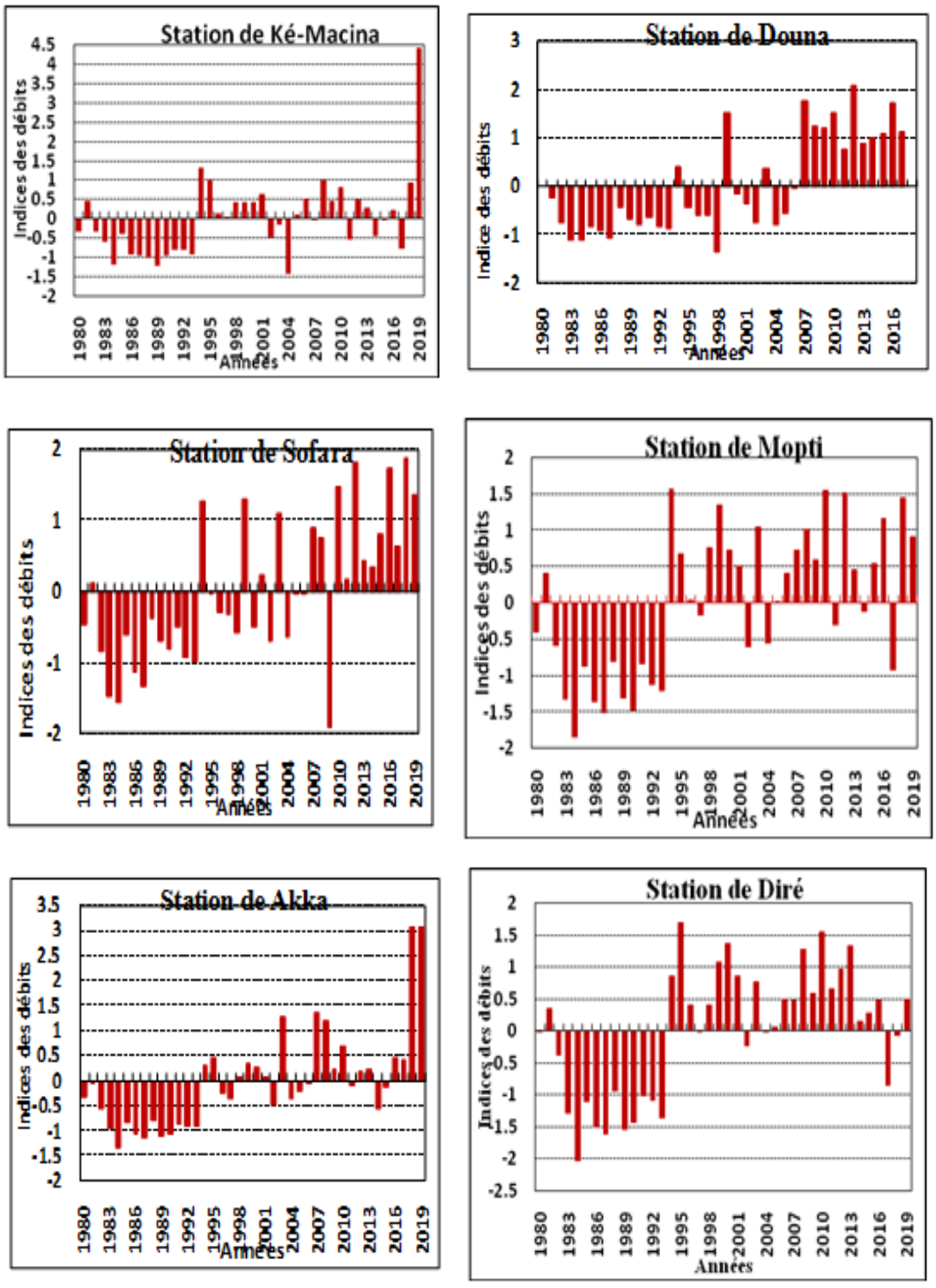


Fig.4 Annual average variations of water flow index of the six hydrological stations during the study period 1980-2019.



At the Mopti hydrological station, from January to May there are the water flows which are below 400 m^3/s and the low water flow is observed in April with 83.19 m^3/s. From June, there is an increase in water flow variations and the peak is reached in October with a value of 2344.87 m^3/s. Beyond the month of October, there is a decrease in flow. At the Akka hydrological station, a decrease in water flow is observed, from January to June,

the low water flow is observed in May with a value of 89.17 m^3/ s. In July there is an increase in the water flow and the peak is reached in November with a value equal to 2339.71 m^3/s. In November, a decrease of the water flow.

At the Dire hydrological station, from January to June, there is a decrease in water variations and the low value of the water with interior Niger flow and the low water flow is observed in May with a value of 55.23 m^3/s. From July, there is an increase in flow and the flood flow is observed during the month of November with a value of 1750.66 m^3/s. Beyond the month of November the water flow decreases with a value.

Annual variations of the water flow index

The annual variation of the water flow index is shown in the figure 4 below.

At the Ke-Macina hydrological station, except for the year 1981, the water flow index variations indicate the period from 1980 to 1993 is a deficit period with the respective index -0.32 and -0.92 on the other hand the period from 1994 to 2018 is a period corresponding a flood flow except for the period 2002-2004 and 2017 the year correspond a low water flow then a dry period. Beyond 2017, there is a wet period. The wettest year is 2018 with an index of 3.18.

At the Douna hydrological station, the water flow index annual variations indicate that the period 1981-2005 with the respective value index -0.26 and -0.56 is a deficit period except for the years 1994, 1999 and 2003 which are flood years. The period from 2007 to 2017 with the index value of 1.77 and 1.11 is a period which corresponds a flood flow then a wet period.

At the Sofara hydrological station, the annual variations of the water flow index give the following observations water index: Except for the year 1981 which is a wet year, the period 1980-1993 is a dry period. Between 1994-2009, there was an alternation of dry and wet periods during the period 1994-2004. Beyond 2009, we have a wet period. The wettest year is 2018 with an index valueof1.9 while the driest year is 2009 with an index value of -1.89.

At the Mopti hydrological station, the 1982-1993 period is a deficit period with the respective values of water flow index to -0.58 and -1.21. The period 1994-2015 is a wet period with respective values of index of 1.56 and 1.16 except for the years 2002, 2004 and 2011 which are deficit years. The water wettest year is 1994 with an index of 1.56 while the dry year is 1984 with a value of water flow index equal to -1,85

At the Akka hydrological station, the period 1980-1997 is a deficit period with respective values water flow index to -0.32 and -0.34 except for the years 1994 and 1995 which are wet years. The period 1994 -2019 is a wet period with respective the values of water flow equal index to 0.33 and 3.1 except for the years 1996, 1997, 2002 and 2014 which are dry years.

At the Dire hydrological station, the period 1982 to 1993 is a period when a low of water flow index is observed with respectively values of water flow index -0.38 and -1.36. From the period 1994 to 2019, there is a period of flood flow with the respective the values of the water flow index equal to 0,85 and 0,49; except the years 2002,2003, 2017 and 2018 which are dry years.

The analysis of the available hydrological data made it possible to identify the variations in the water flows at the entrance, at the center and at the exit of the interior delta of the Niger. The methods for determining the normalized runoff indices of the hydrometric stations in the study area made it possible to identify wet, normal and dry periods.

Of the six (06) hydrological stations, the lowest low water flow was observed at the Douna station in 1998 with a value of 18.94 m^3/s and a flow index of -1.84 and the highest flood flow at the Ke-Macina station in 2019 with a value of 2173.99 m^3/s with a flow index of 4.42.

The period 1981-1993 is a dry period, beyond this period, there is an alternation between dry and wet periods. In 2019 floods were observed the interior Delta of Niger river. From January to June during the study period 1980-2019 there is a decrease in the monthly water flow. The monthly water flow increases from July to reach its maximum in September for the stations of Ke-Macina and Dounaat the entrance of the interior Delta of Niger river. In the center of Delta, the hydrological station of Sofara and Mopti on reach their maximum water flow in October. At the exit of the hydrological stations Akka and Dire hydrological stations reach their maximum their higher water flow in November. The highest monthly water flow is observed at the Ke-Macina station with a value of 3137.74 m^3/s and the lowest monthly flow is observed at the Sofara station with a value of 14.50 m^3/s.

The months of July, August and September correspond to the winter period, during this period the maximum of the plain is flooded.

The shift of the flood month between the six (06) hydrological stations is due to the distance between the stations. The flow takes time from one station to another.

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